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Forecasting storm rainfall over Bhagirathi catchment due to depressions/cyclonic storms

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ABSTRACT. Synoptic typing of systems contributing rainfall in catchment areas has been found to be a useful technique in quantitative precipitation forecasting. This paper contains detailed analysis of 68 rainstorm situations with one day rainfall of 2.5 cm or more over the Bhagirathi catchment during the period 1901-1967 in association with depressions/cyclonic storms. An attempt has been made in this paper to : (*i*) Estimate the contribution of rainfall over the catchment *vis-a-vis* the location of the system; (*ii*) Estimate the intensities of the rainfall *vis-a-vis* the intensities of the causative systems namely depressions/cyclonic storms; (*iii*) Determine the time interval between the origin of the system and its movement to an effective location to cause rainfall over the catchment; (*iv*) Make quick assessment of average areal rainfall over the catchment on the basis of rainfall data from selected key stations, using regression equation and (*v*) Maximize the highest rainstorm of 26 September 1956 by moisture charge method.

1. Introduction

The catchment chosen for the present study is the Bhagirathi catchment. The catchment lies in the border areas of Bihar plateau and Gangetic West Bengal. It has a total area of about 25,000 sq. km. Eastern half of Bhagirathi catchment area consists of flat plains while the western portion has orography of about 150 m amsl and at few places 300 m amsl. The whole catchment area is full of small tributories which quickly transport rainfall water into the main Bhagirathi river and cause flooding. The problem becomes more acute due to heavy discharges in the *Ganga* upstream, *Bhagirathi* often gets heavy floods which affect the downstream area and cause flooding and silting in the river *Hooghly*. The discharges in the river *Bhagirathi* are, therefore, sought to be controlled by barrages at Farakka and at Jangipur 50 km downstream so that the flood discharge on this river at Kalna are regulated and flood crests and troughs smoothened. However, due to flash floods in the tributaries joining *Bhagirathi* above and beyond Jangipur the control has to be exercised at various points to nullify the excess contribution of waters from this catchment. For modulation of flood hydrograph at Kalna, therefore, quantitative estimation of precipitation for the catchment at least for the previous 24-hr and forecasting rainfall quantitatively 24-hr ahead are primary requirements.

This would facilitate the computation of run-off into *Bhagirathi* river from this small catchment for regulating releases of water from above or smoothening the crests and troughs in the river *Hooghly* in order to facilitate navigation. With a view to meet the requirements enumerated above an attempt has been made to study the intensity and durations of rainstorms in the Bhagirathi catchment in relation to the formation and movement of monsoon depressions originating in the Bay of Bengal and land depressions and their movement with particular reference to their location in a two degree grid.

2. Raingauge network

There are 38 raingauge stations in the catchment of which 11 are equipped with self-recording raingauges. In addition to this the State Government authorities also maintain 15 raingauges in the catchment area and their data have been made use of in the present study. This gives the density of raingauge network to about one raingauge for 500 sq. km. Further, the distribution of these raingauges is uniform in the catchment and, therefore, the areal estimation of rainfall in the catchment by arithmatic mean method has been considered to be fairly accurate. The catchment map showing the raingauge stations is given in Fig. 1.

3. Climatological features of the catchment

The annual rainfall over the catchment as a a whole is 136 cm of which 85 per cent occurs during the months of June to October. The coefficient of variation of the annual rainfall is about 20 to 25 per cent over the region which shows that the rainfall is fairly dependable.

The isolyets of rainfall for months June to September and also the annual are shown in Figs. 2(a), (b), (c), (d) and (e) respectively. The monthly as well as the annual isolyetal pattern indicate that the northern and the western areas of the catchment get consistently heavy rainfall as

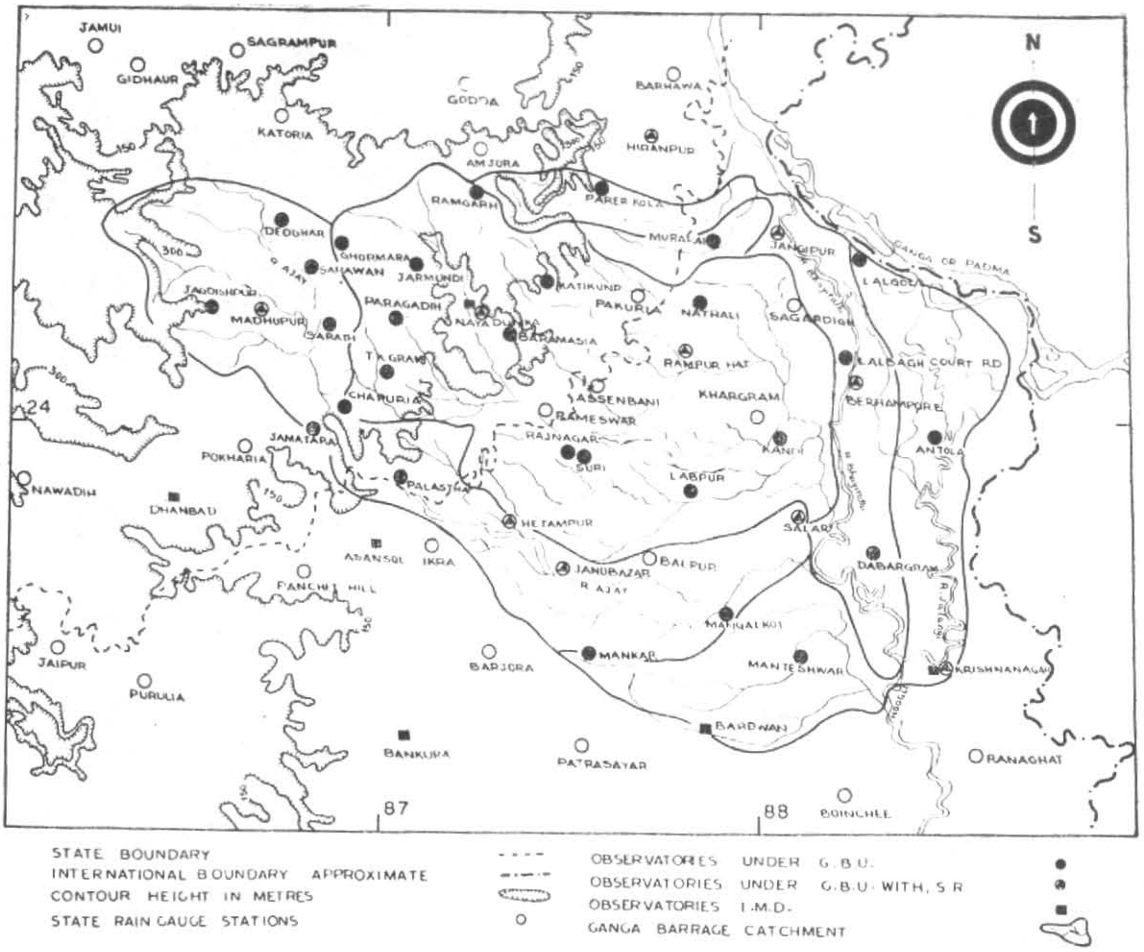


Fig. 1. Contours and raingauge network of Bhagirathi Catchment

compared to its eastern and central portions. This also reveals that maximum monthly normal rainfall of more than 45 cm occurs in the month of July followed by August about 40 cm. The months of June and Septemer the normal remains between 25 and 30 cm. The annual peak rainfall of 174.07 cm occurs at Katikand in northern region of the catchment.

4. Storms listing

The daily rainfall data for the period June to October from 1901 to 1967 have been collected for all the available storms in the catchment. The arithmatic averages of catchment rainfall have been worked out and all these storms which equalled or exceeded the value of 2.5 cm in one day and 1·5 cm on the preceding or succeeding days and 1.0 cm on the subsequent days were picked up. In all there were 238 rainstorms of durations ranging from 1 to 10 days. The rainstorms which were associated directly with cyclonic storms or depressions have been studied in detail and listed in Table 1 along with average rainfall figures over the catchment.

With a view to examine the rainstorms which were in association with depressions and cyclonic storms, *Indian Daily Weather Report* and the storm tracks of the relevant period were consulted and the rainstorms as a result of these weather systems isolated.

5. Depressions/storms — Their location grid and direction of movement

In order to examine depressions and storms which affect the catchment, the area of the Bay of Bengal where the low pressure systems originate and then move inland and the areas comprising the catchment and neighbourhood have been demarcated. The area thus formed has been divided into two-degree latitude and longitude squares and these are 42 in number.

The storms/depressions along with their direction of movement at the time they became effective in contributing storm rainfall in this catchment have been marked in these grids monthwise Figs. 3 (a-e).

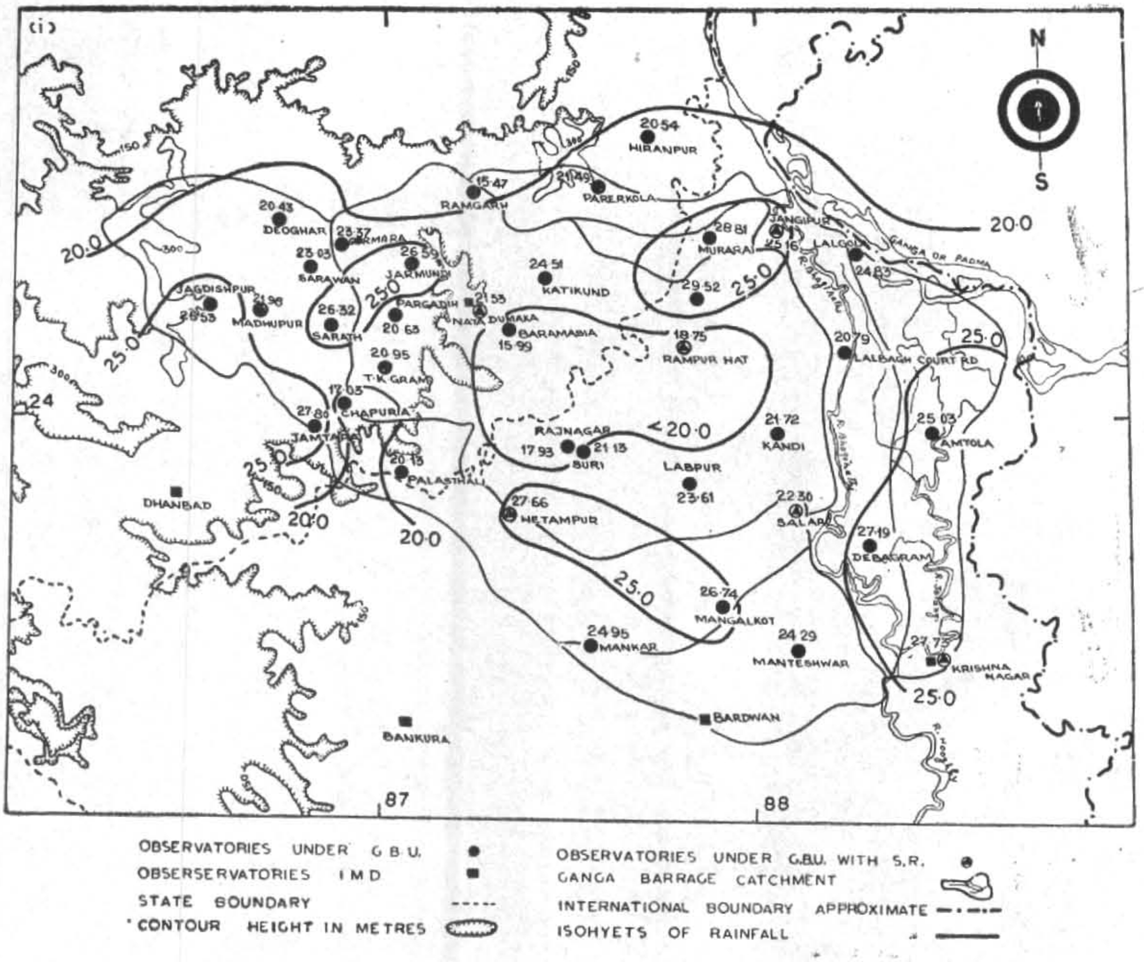


Fig. 2(i). Mean monthly isohyets of rainfall (cm) for the month of June for the Ganga Barrage Catchment

Monthwise statistics of location of storms/ depressions in a particular grid and their directions of movement together with the average depth of precipitation realised in the catchment on the day following their location in a particular grid is given in Table 1. Figs. 3 (a-e) show the storm frequencies *versus* location grid. Out of 238 rainstorms during the period under study, 68 rainstorms only were in association with depressions/ cyclonic storms. The distribution of rainstorms with reference to their duration reveals that the frequency of 2 day storm is maximum, *i.e.*, 33 per cent in the sample of 238 situations. The frequency is 38 per cent for depressions/storms. These are shown in Fig. 4.

Table 3 gives the number of occasions and the average daily depth of precipitation when successive 24 hour catchment rainfall during the duration of the storms was in association with depressions and cyclonic storms that moved through or near the catchment.

It is seen that the catchment is almost evenly prone to depression/cyclonic storm during the monsoon months of June to September and also in October resulting in the realisation of storm rainfall. It is observed that average yield of 24 hr precipitation associated with these systems is between 3.0 and 5.0 cm.

It is significant to note complete absence of cyclonic storms in the month of August and complete absence of land depressions in the month of October, which affected the catchment. This is perhaps due to the fact that the active area over Bay where storms/depressions form shifts further north, the Indo-Gangetic trough is very active and moisture supply copious as also perhaps sufficient time for journey over sea and necessary dynamical conditions for vigorous convective activity of cyclone formation is not available in the month of August while these conditions are reversed in the month of October when the S.W. monsoon is withdrawing from north India. In

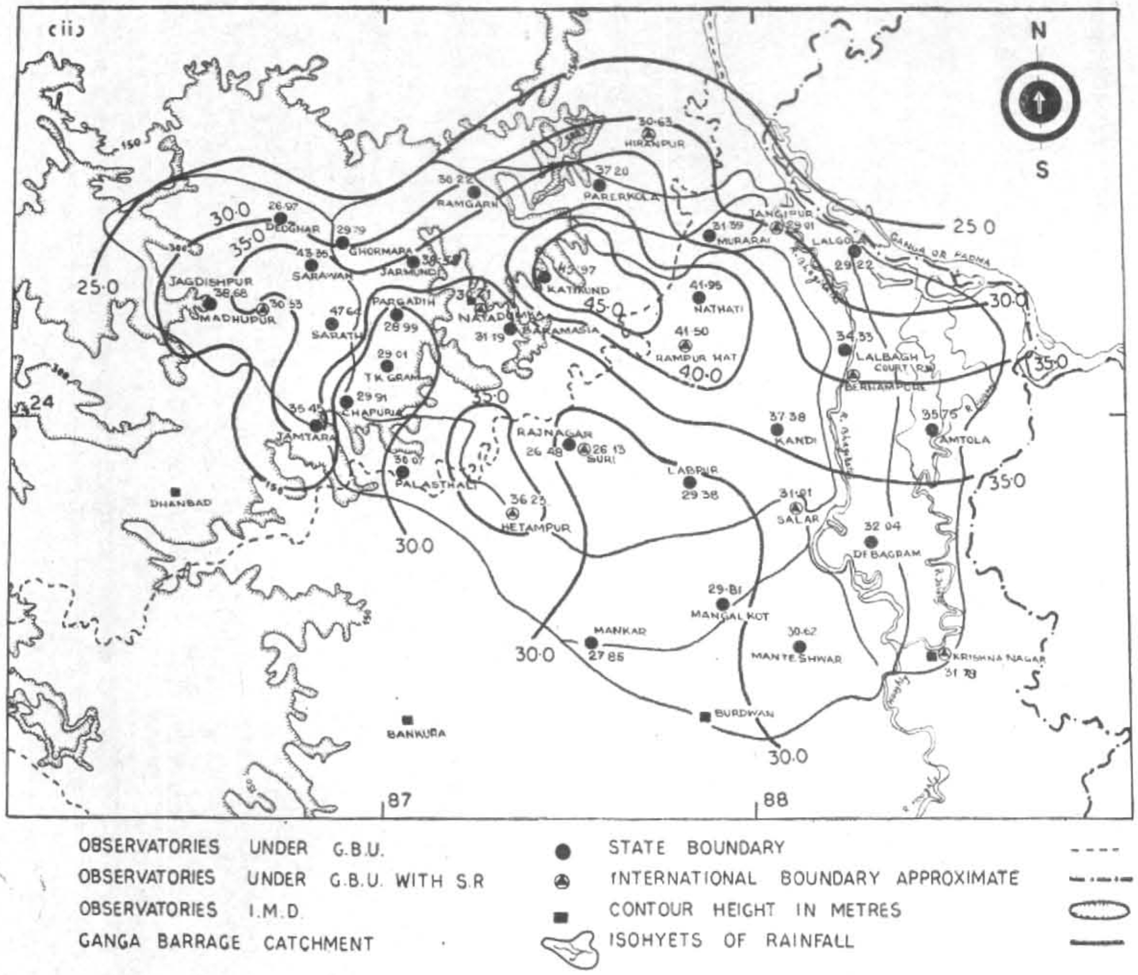


Fig. 2 (ii). Mean monthly isohyets of rainfall (cm) for the month of July for the Ganga Barrage Catchment

October the active area for cyclone/depression formation shifts further south and sufficient time is available for cyclones and depressions to remain over sea for developing and strengthening.

6. Gridwise distribution of cyclonic storms/ depressions

Monthwise frequency of location of storms/ depressions in various grids and their directions of movement have been made.

June — It may be seen from Fig. 3(a) that in the month of June the systems were located in grid Nos. 5, 6, 10, 11, 12, 13, 14, 17, 18, 19, 25 and 26 and moved generally in a northwest or westnorthwesterly direction though a few of them moved in a northerly or northeasterly direction. The maximum number of depressions and storms located in grid No. 17 (head Bay) contributed in average depth of precipitation of 2.0 to 5.0 cm. The systems that were located over or near the catchment, *i.e.*, in grid No. 11 contributed between 3.0 and 7.0 cm of rainfall, depending upon the previous history of the system, its intensity and direction of movement. It is also observed that the highest contribution of catchment rainfall was due to a land depression because of its slow movement and continuous availability of moisture. The other grids were generally ineffective and the location of a depression or storm in them did not contributing storm rainfall in the catchment.

It may, therefore, be inferred that those systems are effective in producing storm rainfall over the catchment on the next day of their location if they are located north of 19°N and between Longs. 82° E & 90° E. The intensity of the rainstorm depends on the associated history of the system. It is noticed that the systems yielded rainfall more than 5.0 cm when they were either over the head Bay or over and near the catchment and were moving towards it. A land depression, however, situated over north Bihar gave as much as 8.6 cm of rain.

July — In the month of July the systems were located in grid Nos. 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 and 20 (Fig. 3b). They moved generally in westnorthwesterly or northwesterly direction. A majority of the systems were located in grid Nos. 16 and 17, *i.e,* in head Bay and con-

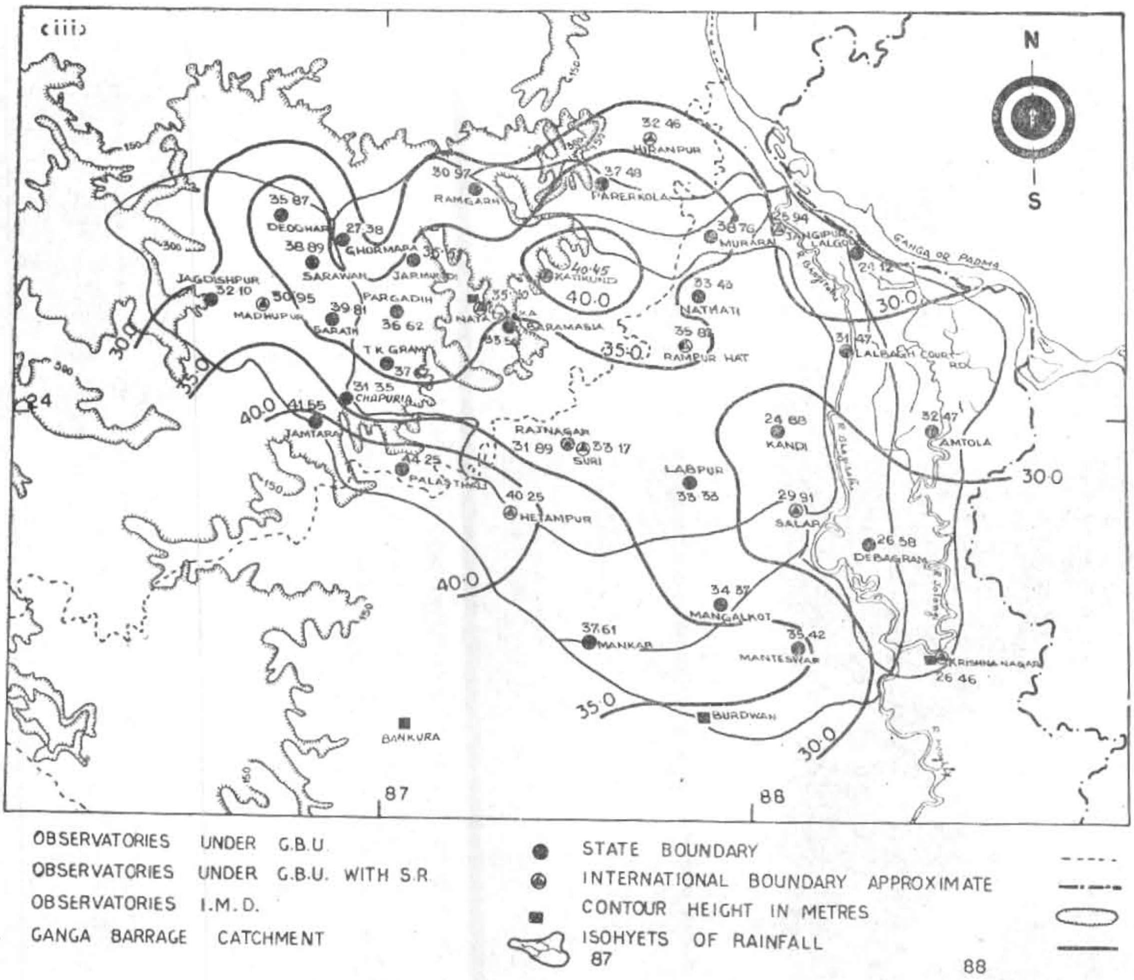


Fig. 2(iii). Mean monthly isohyets of rainfall (cm) for the month of August for the Ganga Barrage Catchment

tributed an average depth of 2.5 cm to 6.0 cm of precipitation. When, however, the systems were located over or near the catchment, the depth of precipitation ranged between 2.5 cm and 9.0 cm depending on the intensity of the system and its direction of movement. It is also observed that when a depression was located in grid No. 10 and moved in a northerly direction, it contributed 8.9 cm of precipitation. A depression situated in grid No. 14 contributed 8.3 cm of precipitation.

The tracks of these depressions/storms were mostly confined in the latitudinal belt from 21°N to 25°N.

In general the storms that can be located north of Lat. 21°N and between Long. 80°E and 94°E have the potentiality of producing storm rainfall in the catchment during the month of July.

It is also noticed that the systems gave more than 5.0 cm of precipitation when they were either over head Bay or near the catchment and were moving towards it. Two sysems, however, located in grid Nos. 14 and 20 gave more than 5.0 cm of rainfall.

August — The month of August was characterised by depressions being located in grid Nos. 5, 6, 10, 11, 12, 13, 14, 16, 17, 18, 19, 21, 23 and 24 (Fig. 3c) and moved generally in a westnorthwesterly or northwesterly direction but showed a more latitudinal scatter. Two depressions located even beyond Long. 80°E over northwest Madhya Pradesh were also found to be effective. In this month also majority of the storms were located in grid No. 17, *i.e.*, head Bay. The 24-hr average depth of precipitation realised was between 2.0 and 6.0 cm. In this month also a land depression was located in grid No. 11 moving in a westnorthwesterly direction, contributed 9.7 cm of catchment rainfall. The systems that become effective in causing storm rainfall in the catchment on the day following their formation in the effective grids were located north of Lat. 19° N and west of Long. 92 °E.

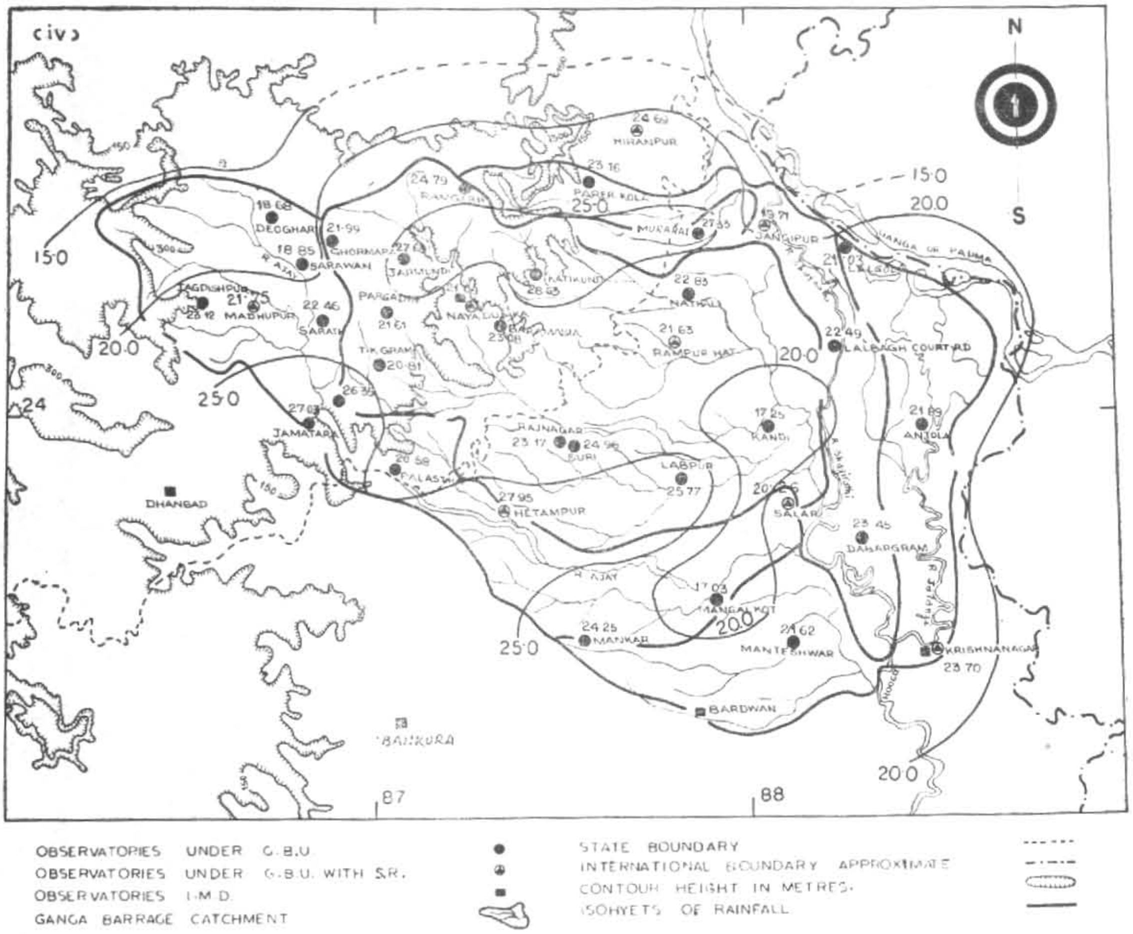


Fig. 2(iv). Mean monthly isohyets of rainfall (cm) for the month of September for the Ganga Barrage Catchment

It is seen that during this month land depressions over and near the catchment gave as much as 6.0 to 10.0 cm of precipitation.

September — In the month of September, 34 depressions/cyclonic storms were located in grid Nos. 5, 6, 10, 11, 12, 16, 17, 18, 19, 20, 23, 24, 25, 26 and 31 (Fig. 3d) though majority of them were confined to the grid Nos. 17, 18 and 24. The systems operated in an area generally bounded by Lat. 19° N - 25°N and Long. 82° E - 92°E, they moved generally in a northwesterly to westnorthwesterly direction though a few of them took a northerly course.

October — In the month of October the grids that were effective in producing storm rainfall on the day following their location in a particular grid were 13, 17, 18, 19, 20, 25, 26, 27, 31, 32, 33, 34, 35 & 41 (Fig. 3 e). They moved generally between northwest and northeast direction. The systems were effective when they were located north of Lat. 15° N and west of Long. 90° E. 24 per cent of the 29 events in the month having appeared in grid Nos. 19 and 20 gave an average of 3·6 cm of rainfall in the catchment and a depression centred on grid No. 19 gave as much as 9·9 cm of average rainfall.

It is also observed that in this month the systems were located in grid Nos. 19, 20, 27 and 35 and except for one were moving in a northeasterly direction and gave more than 5·0 cm of rain.

As may be seen from Table 2 that 20 storms/depressions out of 23, which gave rainfall more than 5 cm on next day had northerly component in their movement and the two depressions/land depressions having a southerly component in movement were located west/northwest of the catchment. The grid distribution of these storms/depressions is such that the catchment remains under the influence of these systems for a greater period and also that with the advance of the months from June to October even systems in the move southerly and southwesterly grids became effective in giving rainfall more than 5 cm. In the month of October as much as 4 out of 5 depressions move NE to give rainfall greater than

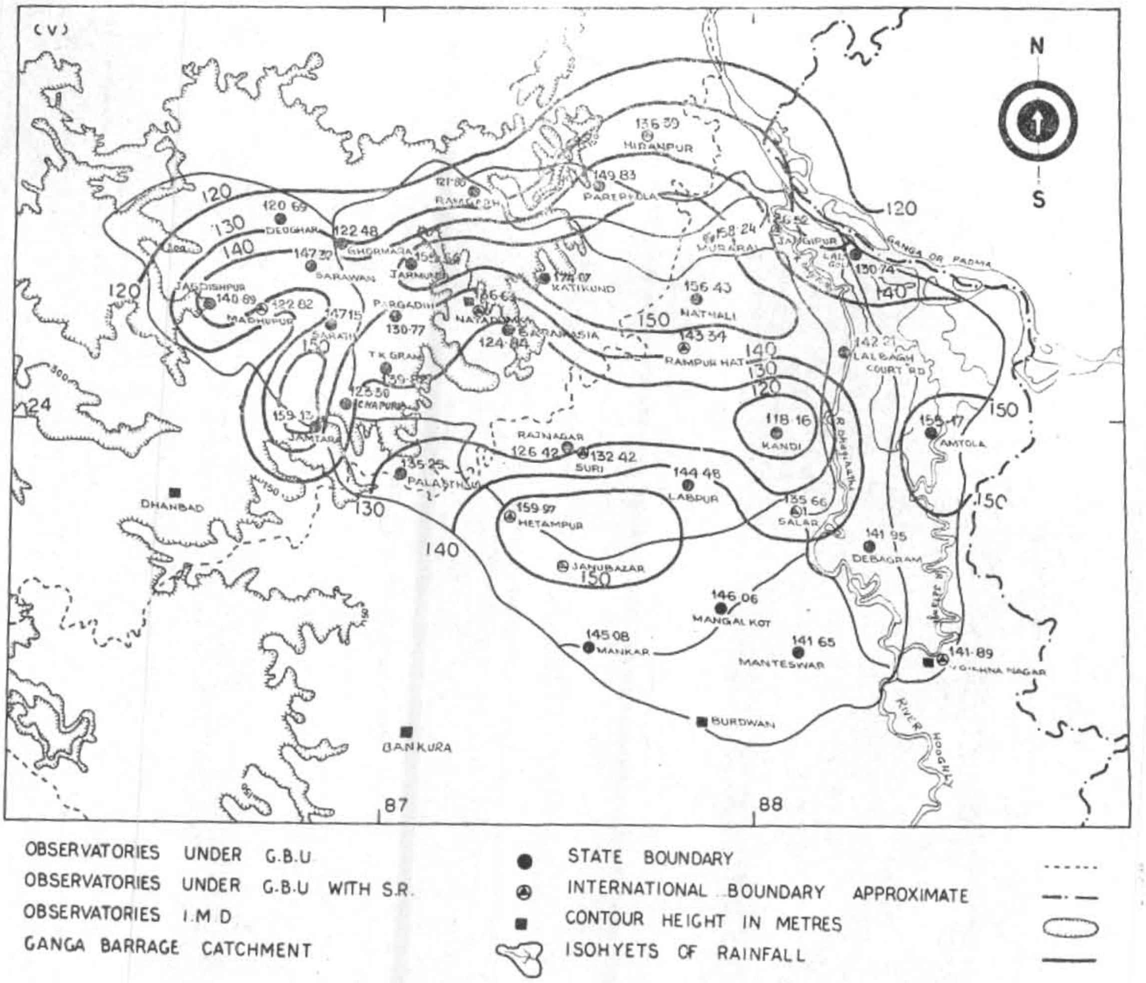


Fig. 2(v). Mean annual isohyets of rainfall (cm) for the Ganga Barrage Catchment

5 cm in the catchment. It may be seen that the highest rainfall of 9·9 cm was realised in October when the depression in grid No. 19 to the SW of catchment moved NE.

It may be summarised that systems when they located are either in the head Bay or near the catchment and are moving towards it are likely to yield more than 5·0 cm.

7. Place of origin of storms/depressions and their travel time to reach an effective grid

Though most of the cases described in the foregoing section have provided only about 24-hr time interval, there have been significant instances of two to three days interval between the birth of a system and its entry into an effective grid thus providing an useful forecasting element in predicting the catchment rainfall in advance. Table 5 gives the frequency of instances of such storms, their directions of movement and travel time to reach an effective grid.

In the month of June a system forming within Lats. 15° N–17°N and Longs. 84° E–90° E moving initially in a northwesterly direction and then recurving towards north or northeast has a travel time of about 4 days and on entering grid No. 25, *i.e.*, crossing Lat. 19° N is likely to produce storm rainfall. Systems forming north of Lat. 17° N and moving in a northwesterly direction are likely to take 24 hours to reach an effective grid.

In the month of July systems forming near about Lat. 17° N and Long. 86° E and moving in a northwesterly direction towards Orissa coast and then moving north may take about 3 days to enter an effective grid No. 19. While a system forming further east of Long. 86° E and taking a more northerly course may take about 2 days and that forming near about Lat. 20° N and Long. 92° E and moving in a northerly direction may take about 24 hours only to reach an effective grid.

In the month of August systems originating at about Lat. 18° N and to the west of Long. 87°E moving initially in a northnorthwesterly direction and then recurving towards northeast may take about 2 days to reach an effective grid and

TABLE 1

S. No.	Storm period	Day	Classificatoin of storm/dep.	Position (grid No.)	Directon of movement	*Rainfall on the next day (cm)
	June (1901-1967)					
1	18-21 Jun 1907	17	S	25	NE	3·0
		18	S	17	NW	3·8
		19	D	11	NW	5·6
		20	D	12	WNW	1·7
2	6-10 Jun 1909	5	LD	26	N	2·9
		6	LD	19	NW	3·5
		7	LD	13	N	2·5
		8	LD	6	N	4·2
		9	LD	5	N	8·6
3	11-15 Jun 1911	10	S	25	NW	2·1
		11	D	26	NNW	4·6
		12	D	13	NE	3·6
		13	D	12	ESE	6·8
		14	D	11	ENE	6·8
4	17 Jun 1911	16	SD	17	NW	3·2
5	19-20 Jun 1911	18	D	17	NW	2·9
		19	D	18	NW	2·1
6	13-15 Jun 1917	13	D	17	WNW	2·7
		14	D	14	WNW	1·8
7	4-5 Jun 1922	3	D	—	—	3.2
		4	S	11	NW	3·5
8	13-15 Jun 1922	12	S	17	NW	4·5
		13	S	17	NW	4·7
		14	S	17	Stationary	4·9
9	11-12 Jun 1950	10	S	17	N	4·1
		11	D	11	NW	5·9
10	28-30 Jun 1966	28	SD	17	N	3·0
		29	D	10	N	4·3
	Total	28 (5LD, 13D, 8 S and 2SD)				
	July (1901-1967)					
1	14 Jul 1905	13	D	11	NW	2·9
2	27-30 Jul 1905	27	D	16	NW	5·6
		28	D	10	N	8·9
		29	D	10	—	1·7
3	30-31 Jul 1909	29	D	18	—	2·9
		30	D	18	—	1·7
4	3-5 Jul 1914	2	D	16	NW	2·6
		3	D	10	W	5·5
		4	D	12	NW	2·8
5	27-28 Jul 1921	26	S	17	NNW	3·6
		27	S	17	NW	6·5
6	3-4 Jul 1930	2	LD	13	W	2·5
		3	LD	14	W	3·7
7	7-9 Jul 1930	7	SD	—	—	3·2
		8	SD	10	NW	3·1
8	17-19 Jul 1930	16	S	15	NW	2·5
		17	S	16	WNW	3·6
		18	D	17	WNW	4·8
9	25-27 Jul 1936	24	D	19	NW	1·5
		25	D	20	NNW	3·7
		26	D	13	NNW	3·1
10	29 Jul 1942	28	D	17	W	2·7
11	14-17 Jul 1943	13	DD	20	WNW	1·9
		14	DD	20	WNW	5·3
		15	D	14	WNW	8·3
12	9-12 Jul 1959	10	D	16	NW	4·8
		11	D	11	W	2·5
	Total	27(2LD, 17D, 4S, 2SD and 2DD)				
	August (1901-1967)					
1	10-11 Aug 1902	9	LD	12	—	3·1
2	29-31 Aug 1909	29	LD	11	WNW	9·7
		30	LD	12	NNW	4·5
3	9-11 Aug 1911	10	LD	13	—	2·7
4	6-8 Aug 1913	6	LD	16	NW	4·9
		7	LD	10	WNW	3·5
5	20-27 Aug 1918	24	LD	5	—	4·9
		25	LD	5	S	6·1
		26	LD	12	W	1·8
6	16-19 Aug 1921	18	LD	5	—	1·8
7	30 Aug-5 Sep 1926	4	LD	11	W	2·6
8	2-3 Aug 1928	1	D	23	NW	1·7
		2	D	17	NW	3·9
9	17-22 Aug 1933	21	LD	12	WNW	2·2
10	6-10 Aug 1936	8	LD	6	—	2·0
11	27-28 Aug 1940	26	D	17	WNW	1·9
		27	D	17	NNW	3·2
12	25-26 Aug 1941	25	LD	17	NW	3·1
13	31 Aug-5 Sep 1942	30	D	24	NW	2·7
		31	D	19	WNW	1·5
		1	D	21	NW	1·5
		2	D	14	NNW	4·5
		3	D	..	NNW	5·3
		4	D	..	NW	1·8
14	10-12 Aug 1950	9	D	17	WNW	2·0
		10	D	11	WNW	2·6
		11	D	11	WNW	2·2
15	17 Aug 1956	16	D	24	NNE	2•9
16	2-4 Aug 1959	3	LD	10	WNW	3•0
17	25 Aug 1965	24	D	18	NW	3·3
	Total	30 (15LD & 15D)				

*Rainfall recorded at 0830 IST of next day of the day mentioned in Cols. 3 and 10

SS=Severe Cyclonic Storm, S=Cyclonic Storm, DD=Deep Depression

D=Depression, SD=Shallow Depression, LD=Land Depression.

TABLE 1 (*contd*)

S. No.	Storm period	Day	Classification of storm/dep.	Position (grid No.)	Direction of movement	*Rainfall on the next day (cm)
September (1901-1967)						
1	8-10 Sep 1902	8	S	17	NW	7·0
2	25-26 Sep 1902	24	D	24	NW	4·2
		25	D	18	NW	3·6
3	14-16 Sep 1905	14	LD	5	S	4·5
		15	LD	5	Filling	2·4
4	9-13 Sep 1920	8	D	25	NNW	2·4
		9	D	18	NW	7·8
		10	D	12	NW	2·4
5	22 Sep 1935	21	D	18	N	3·2
6	29-30 Sep 1937	28	SS	17	N	3·5
		29	S	10	NW	5·9
7	7-8 Sep 1941	6	SD	23	WNW	3·8
		7	D	24	NW	1·7
8	30 Sep-1 Oct 1945	29	D	31	NW	3·0
		30	D	26	NW	1·8
9	10-11 Sep 1946	10	D	16	WNW	2·2
10	16-17 Sep 1946	15	D	17	NNW	1·9
		16	D	17	NW	5·1
11	10 Sep 1951	9	LD	16	WNW	3·6
12	27-28 Sep 1953	26	D	24	NW	3·7
		27	D	18	NW	1·5
13	14-16 Sep 1958	13	D	17	NW	1·5
		14	D	17	NW	2·5
		15	D	11	W	2·6
14	7-14 Sep 1959	10	LD	19	WSW	3·7
		11	LD	19	WSW	2·3
		12	LD	20	WSW	1·5
		13	LD	20	W	1·9
15	23-24 Sep 1961	22	D	17	NW	4·9
		23	D	18	NW	1·6
16	22-23 Sep 1962	21	S	18	NW	4·5
		22	S	6	WNW	4·0
17	27-28 Sep 1963	26	D	24	WNW	3·1
		27	D	18	NW	3·1
Total	34 (7LD, 1SCS, 1SD, 21D and 4S)					

S. No.	Storm period	Day	Classification of storm/dep.	Position (grid No.)	Direction of movement	*Rainfall on the next day (cm)
October (1901-1967)						
1	6 Oct 1911	5	D	18	Dissipated	3·1
2	2-4 Oct 1916	2	D	32	NW	3·9
		3	D	27	NW	2·4
3	5-7 Oct 1917	4	D	26	NW	2·6
		5	D	20	NW	6·3
		6	D	20	NE	4·6
4	7-8 Oct 1928	6	D	13	NE	2·1
		7	D	13	—	3·7
5	5-8 Oct 1929	4	D	41	NNE	2·2
		5	D	34	NE	2·6
		6	D	27	NE	4·2
		7	D	19	NE	4·3
6	18-20 Oct 1929	17	S	33	NNE	3·2
		18	D	26	NE	3·6
		19	D	26	NE	2·1
7	23-24 Oct 1932	22	D	33	NNW	2·0
		23	D	20	NE	3·4
8	5-6 Oct 1936	4	S	25	NW	2·3
		5	D	19	NE	2·8
9	8-11 Oct 1941	8	D	27	NE	5·8
		9	D	19	NE	9·9
		10	D	19	NE	1·8
10	16-18 Oct 1942	15	S	31	NNW	3·2
		16	SS	18	NNE	3·6
		17	S	18	NE	2·2
11	21-22 Oct 1945	20	D	35	NE	5·5
		21	D	20	NE	5·6
12	5-6 Oct 1946	4	D	31	NNW	3·3
		5	D	17	NE	2·7
Total	29 (24D, 4S, 1SCS)					

*Rainfall received at 0830 IST of the next day of the day mentioned in Cols. 3 and 10

SS=Severe Storm, S=Cyclonic Storm, DD= Deep Depression

D=Depression, SD=Shallow Depression, LD= Land Depression.

a system forming between 17° N to 19° N and about 90° E moving in a northwesterly direction may take 24 hours only to reach an effective grid.

In the month of September most of the systems originating in the area bounded by Lats. 17°N to 19°N and Longs. 88° E to 92° E and moving in a northwesterly or northnorthwesterly direction become effective after a travel time of 24 to 48 hrs. A system forming further south of Lat. 17° N took 3 days to become effective. A system originating near Arakan coast south of Lat. 17° N moving initially in a northwesterly direction may take about 2 days to become effective.

It may be inferred, therefore, that systems originating between Lats. 17° and 19°N in the Bay take 24 to 48 hr depending upon the direction of movement to reach a point when storm rainfall can be realised on the next day. Systems forming south of Lat. 17° N and between Longs. 90° E and 94° E may take about 3 days to enter an effective grid.

TABLE 2

Grid location of storms/depressions and their direction of movement when the storm rainfall was 5.0 cm or more

S. No.	Storm period	Day	Classification of Storm/dep.	Position (grid No.)	Direction of movement	Rainfall on the next day (cm)
		June				
1	18-21 Jun 1907	19	D	11	NW	6·0
2	6-10 Jun 1909	9	LD	5	N	3·6
3	11-15 Jun 1911	13	D	12	ESE	6·8
		14	D	11	ENE	6·8
4	11-12 Jun 1950	11	D	11	NW	5·9
		July				
1	27-30 Jul 1905	27	D	16	NW	5·6
		28	D	10	N	8·9
2	3-5 Jul 1914	3	D	10	W	5·5
3	27-28 Jul 1921	27	S	17	NW	6·5
4	14-17 Jul 1943	14	DD	20	WNW	5·3
		15	D	14	WNW	8·3
		August				
1	29-31 Aug 1909	29	LD	11	WNW	9·7
2	20-27 Aug 1918	25	LD	5	S	6·1
3	31 Aug-3 Sep 1942	3	D	(Outside NNW grid)		5·3
		September				
1	8-10 Sep 1902	8	S	17	NW	7·0
2	9-13 Sep 1920	9	D	18	NW	7·2
3	29-30 Sep 1237	29	S	10	NW	5·9
4	16-17 Sep 1946	16	D	17	NW	5·1
		October				
1	5-7 Oct 1917	5	D	20	NW	6·3
2	8-11 Oct 1941	8	D	27	NE	5·8
		9	D	19	NE	9·9
3	21-22 Oct 1945	20	D	35	NE	5·5
		21	D	20	NE	5·6

TABLE 4 (a)

Rainstorm	Date	Systems		Dir. of movement	Av. pptn. (cm) in catchment on the following day
		Description	Location grid		
(1) 25 Aug 1965	24	D	18	NW	3·3
(2) 28-30 Jun 1966	28-29	SD.D	17, 10	N.N	1·5, 3·0
(3) 11-15 Jun 1911	13	D		ESE	6·8
18-21 Jun 1907	20	D	12	WNW	1·7
(4) 27-30 Jul 1905	28	D		N	8·9
7-9 Jul 1930	8	D	10	NW	2·1
(5) 29-31 Aug 1909	29	LD		WNW	9·7
10-12 Aug 1950	10	D	11	WNW	2·6
(6) 9-13 Sep 1920	9	D		NW	7·2
27-28 Sep 1953	27	D	18	NW	1·5
(7) 8-11 Oct 1941	9	D		NE	9·9
5-6 Oct 1936	5	D	19	NE	2·8

TABLE 4 (b)

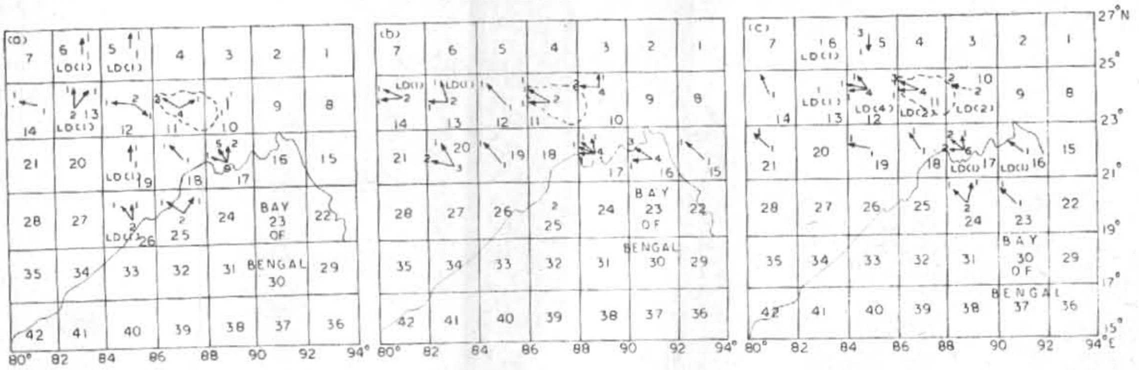
Case No. and date	System	Press. dep. from normal (mb)	Central pressure (mb)	Cyclonic circulation upto km (a.s.l.)
1. 23 Aug 1965	D	2·0	1000	6.0
24 Aug 1965	D	4·0	998*	4·5
25 Aug 1965	D	1·0	1002	0·9
2. 27 Jun 1966	D	4·0	996	5·4
28 Jun 1966	D	6·0	994	7·2
29 Jun 1966	D	4·0	996	7·2
30 Jun 1966	D	2·0	996	2·1

TABLE 4 (c)

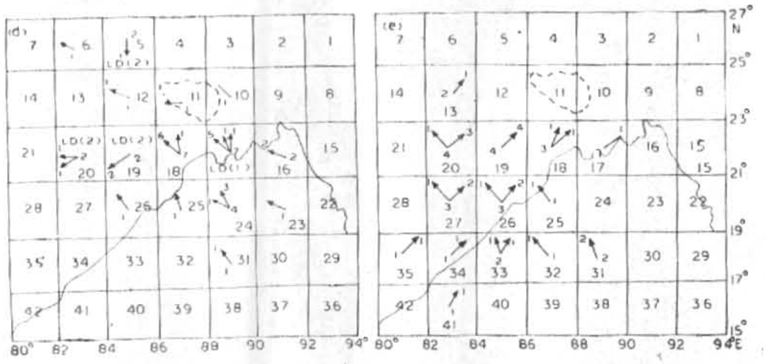
Case No.	Date	Classification of system	Direction of movement	Associated rainfall
3(a)	13 Jun 1911	D	ESE	6·81
3(b)	20 Jun 1907	D	WNW	1·65
5(a)	29 Aug 1909	LD	WNW	9·75
5(b)	10 Aug 1950	D	WNW	2·64

TABLE 3

Month	Cyclonic storm	Average 1-day rainfall (cm)	Depression	Average 1-day rainfall (cm)	Land depression	Average 1-day rainfall (cm)	Total
Jun	8	3·8	15	3·8	5	4·3	28
Jul	4	4·1	21	3·6	2	3·1	27
Aug	..	..	5	2·7	15	3·7	20
Sep	5	5·0	22	2·9	7	2·9	34
Oct	5	2·9	24	3·8	..	..	29
Total	22		87		29		138



(a) June (b) July (c) August



(d) September (e) October

Figs. 3 (a-e). Frequency of direction of movement of effective storms & depressions *vs* location grid (1901-1967)

The place of origin for storms in the month of October is generally between Lats. 8° N and 14° N near the Andaman Sea. They initially move in a northwesterly direction. Most of them afterwards recurve and move towards northeast.

The travel time for the storm forming between Lats. 13° N-15° N and moving in a northwesterly direction take about 3 to 5 days to reach an effective grid after crossing Lat. 17° N. A system moving north from south of Lat. 17° N become effective only after crossing lat. 19° N. Another system forming north of Lat. 15° N and within a degree of Long. 91° E and moving north may become effective after one day only.

A system forming as far south as betwen 7° N and 9° N moving fast initially in a northwesterly direction and then recurving become effective after crossing Lat. 15° N in about 3 to 5 days. Storm history in respect of those systems whose origins could be located prior to their entering an effective grid is given in Table 5.

8. Orientation of effective grids

A comparative study of the effective grid diagrams Figs. 3 (a to e) shows north-south orientation in the month of June with scatter to east, south of 25° N and to west, north of 23° N while the orientation in the month of July has become east-west along about 23° N. The orientation in the month of August has become northwest to southeast. The orientation in the month of September is also east-west but between the Lat. belt 21° N and 23° N there is a northwest to southeast scatter. In the month of October the effective grids have shown a remarkable shift to the southwest of the catchment under study and are mainly confined in an area bounded by 17° N to 23° N and 82° E to 90° E which can give a clue to the forecaster as to where a cyclonic storm/depression in a particular month is capable of giving storm rainfall in this catchment. This obviously reveals the relationship between the seasonal trough *vis-a-vis* the location of storm/depression and consequent rainfall in the catchment which has to be borne in mind while forecasting the storm rainfall in this catchment.

9. Duration and intensity of rainstorms *vis-a-vis* synoptic features

The under mentioned cases of marked differences in the intensity and duration of the rainstorms have been selected for studying the special meteorological features associated with the rainstorms with respect to the intensity of the systems like upper air structure, gradient of pressure departures, movement of the systems towards or away from the catchment. Cases 1 and 2 pertain to the duration of the rainstorms. The systems were located in different grids. Cases 3 to 7 pertain to the intensity of the rainstorms even though the systems were located in the same grids.

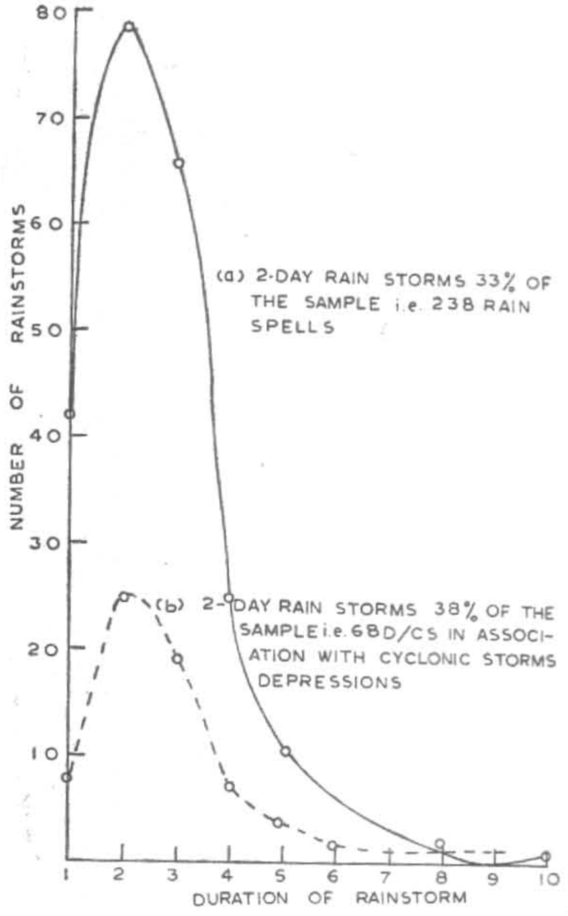


Fig. 4. Frequency of occurrence of rainstorm (1901-67)

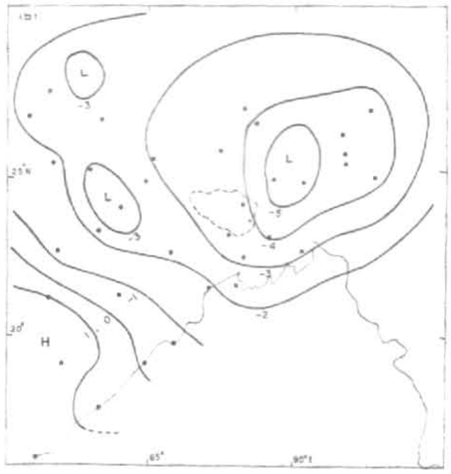


Fig. 5(b). 8 Jul/9 Jul 1930, 3.1 cm

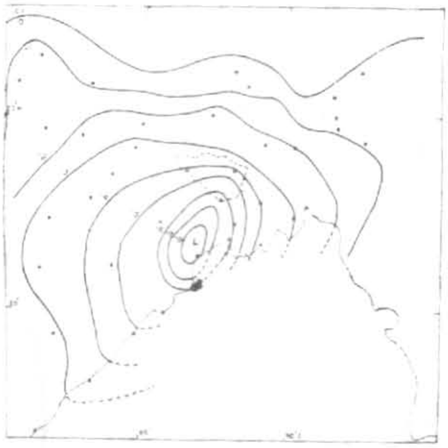


Fig. 5(c). 9 Sep/10 Sep 1920, 7.2 cm

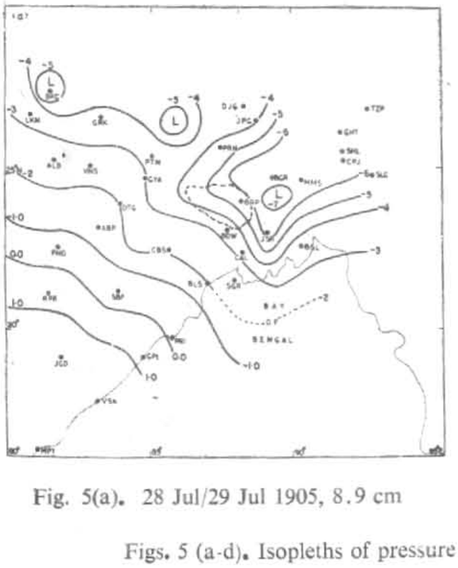
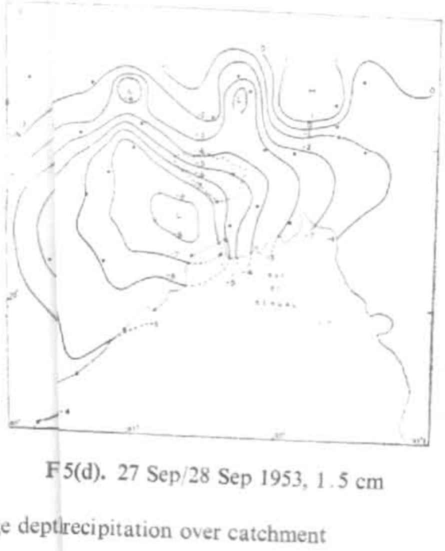


Fig. 5(a). 28 Jul/29 Jul 1905, 8.9 cm



F 5(d). 27 Sep/28 Sep 1953, 1.5 cm

Figs. 5 (a-d). Isopleths of pressure departure/average depth precipitation over catchment

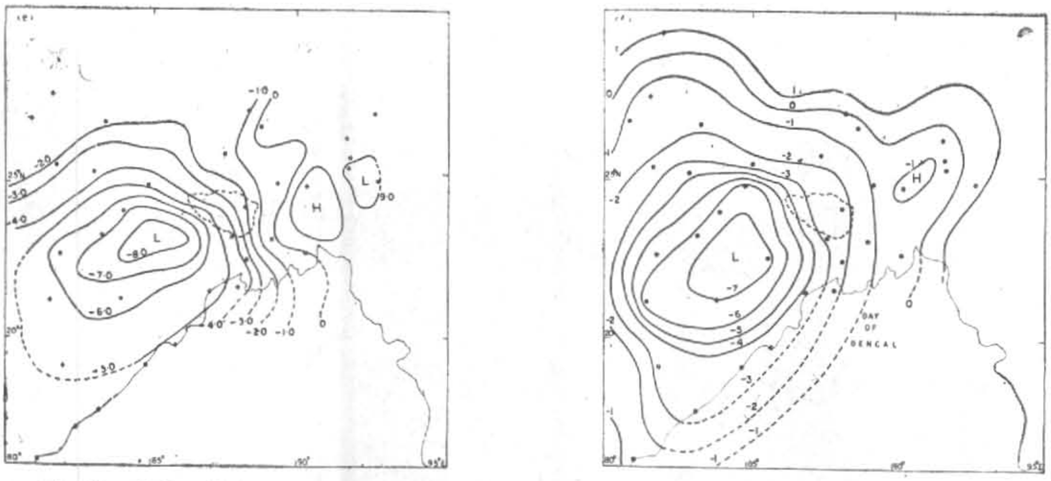


Fig. 5(e). 9 Oct/10 Oct 1941, 9.9 cm

Fig. 5(f). 5 Oct/6 Oct 1936, 2.8 cm

Fig. 5 (e-f). Isopleths of pressure departure/average depth precipitation over catchment

Cases 1 & *2*—Attendant meteorological situations which were responsible for causing 1-day and 3-day rainstorms were examined. The salient surface and upper air features are given in Table 4 (b).

A revealing feature of the two systems was their respective speeds of movement, while the system associated with the 3-day storm was practically stationary on 27 June which helped in its further intensification on 28 June, the system associated with 1-day storm of 25 August 1965 moved away speedily from the catchment area on the same day with a speed of 25 km per hour.

Cases 3 & *5* — Intensity of rainstorm *vis-a-vis* direction of movement of the causative system may be seen in Table 4 (c). On 13 June the depression having recurved was centred near Hazaribagh and was moving in a eastsoutheasterly direction towards the catchment and was centred near Burdwan on 14th. During its movement towards and through the catchment a rainstorm of the magnitude of 6.8 cm was realised on the following morning. Similarly, the high rainstorm of 29 August 1909 was as a result of a land depression centred near Behrampore and moving towards the catchment in a westnorthwesterly direction. The low precipitation yield associated with the cases at 3(b) and 5(b), the depressions were moving away from the catchment. In the first instance a depression centred near Hazaribagh on 20th was moving away from the catchment in a westnorthwesterly direction and in the second instance a depression moved away in northwesterly direction towards east Uttar Pradesh.

10. Analysis of rainstorms

Rainstorms depending upon the range of pressure departures — Analysis of pressure departures (pressure defect) on the previous day to that of the storm rainfall in association with depressions and cyclonic storms revealed that the range of pressure defect over and very near to the catchment area is a favourable parameter for estimating the intensity of rainfall. It was also noticed that in case of fast moving storms near or through the catchment since the higher range of pressure defect lasted relatively for shorter duration over catchment, the rainfall contribution was also less while in cases where the storms/depressions remained practically stationary or moved in such a way that the catchment was continuously under the influence of that much pressure defect the rainfall contribution was much more.

Six typical cases, one each of heavy and small storm rainfall in the catchment area in the months of July, September and October are shown in Figs. 5(a to f) respecitvely.

Fig. 5(a) shows isopleths of pressure departures on 28 July 1905 and associated catchment rainfall of 8.9 cm on 29 July 1905 where the pressure departure ranged between 3 and 6 mb over the catchment and it was continuously in the influence of the depression during the period while the isopleths of pressure departure Fig. 5(b) of 8 July 1930 reveal hardly a range of 1 mb over the catchment area and the associated rainfall was also relatively small (*viz.*, 3.1 cm) as recorded on next day.

Isopleths of pressure departures on 9 September 1920 (Fig. 5c) reveal a range of pressure defect of about 3 mb over the catchment and rainfall recorded at the next day 7.2 cm while those of 27 September 1953 (Fig. 5d) also reveal a pressure defect of about 3 mb over the catchment but very less rainfall (*i.e.*, 1.5 cm) recorded next day. Here the storm had decreased rapidly in intensity and moved fast along the seasonal trough and could

TABLE 5

Place of origin of storms/depressions and their travel time to reach an effective grid

Serial No.	Storm period	Day	System	Position of system		Direction of movement	Effective grid	Travel time	Average catchment rainfall
				Lat. (°N)	Long. (°E)			(hr)	(cm)
1	18-21 Jun 1907	13	D	15·5	85·0	NW			
		14	SS	16·5	84·5	N			
		15	SS	17·5	84·5	NE			
		16	SS	18·5	85·5	NE			
		17	SS	20·0	87·5	NE	25	96	2·5
2	10-14 Jun 1911	9	SS	18·0	88·5	NW			
		10	SS	19·5	86·5	NW	25	24	2·1
3	11-12 Jun 1950	9	D	18·5	90·5	NW			
		10	SS	21·5	88·5	N	17	24	4·1
4	27-28 Jul 1921	24	SS	18·5	89·5	N			
		25	SS	19·5	89·5	N			
		26	S	21·5	89·0	NNW	17	48	3·6
5	17-19 Jul 1930	15	S	20·5	92·0	N			
		16	S	22·0	92·0	NW	15	24	2·5
6	25-27 Jul 1936	21	D	18·0	87·0	NW			
		22	—	..	..	—			
		23	D	19·0	85·5	NW			
		24	D	21·5	84·5	NW	19	72	1·5
7	31 Aug-5 Sep 1942	29	D	18·5	90·0	NW			
		30	D	19·5	88·5	NW	24	24	2·7
8	17 Aug 1956	14	D	18·0	88·0	NW			
		15	D	18·5	87·5	NNE			
		16	D	20,5	88·5	N	24	48	2.9
9	25-26 Sep 1902	23	D	18·0	90·0	NNW			
		24	D	20·5	89·0	NW	24	24	4·2
10	9-13 Sep 1920	6	D	17·0	90·0	NW			
		7	D	18·0	88·0	NNW			
		8	D	19·5	87·5	NNW	25	48	2·4
11	29-30 Sept 1937	26	D	16·5	94·0	NW			
		27	D	18·0	90·0	NW	17	48	3·5
		28	SS	21·5	88·0	N			
12	27-28 Sep 1953	23	D	16·0	91·0	NW			
		24	D	16·5	90·0	NW			
		25	D	18·0	88·0	N			
		26	D	20·5	88·0	NW	24	72	3·7
13	22-23 Sep 1962	20	D	21·5	90·0	NW			
		21	S	22·5	89·5	NW	18	24	4·5
14	27-28 Sep 1963	25	D	17·5	93·0	NW			
		26	D	19·5	90·0	NW	24	24	3·1
15	7-8 Oct 1928	1	D	14·5	93·5	NW			
		2	D	17·5	89·5	NW			
		3	S	19·5	85·5	NW			
		4	D	22·5	81·5	NNE			
		5	D	23·0	82·0	NE			
		6	D	23·5	83·5	NE	13	120	2·1
16	5-8 Oct 1929	2	D	12·0	85·0	NW			
		3	D	14·0	83·5	NW			
		4	D	16·0	82·5	NNE	41	48	2·2
17	23-24 Oct 1932	19	D	14·0	97·0	NW			
		20	D	14·5	93·0	NW			
		21	S	16·0	88·5	NW			
		22	D	18·5	84·0	NNW	33	72	1·2
18	8-11 Oct 1941	4	D	6·5	87·5	NW			
		5	D	9·0	84·0	NW			
		6	D	13·5	81·5	NNE			
		7	D	16·0	82·0	NNW			
		8	D	19·2	82·5	NE	27	96	5·8

TABLE 5 (*contd*)

Serial No.	Storm period	Day	System	Position of system		Direction of movement	Effective grid	Travel time	Average catchment rainfall
				Lat. (°N)	Long. (°E)			(hr)	(cm)
19	16-18 Oct 1942	14	D	17·0	90·5	NW			
		15	S	18·0	88·5	NNW	31	24	3·2
20	20-21 Oct 1945	15	S	7·5	91·0	NW			
		16	S	10·0	87·5	NW			
		17	SS	14·0	84·0	NW			
		20	D	..	..	NE	35	120	5·5
21	4-5 Oct 1946	3	D	16·0	91·5	NW			
		4	D	18·0	88·0	NNW	31	24	3·3

Severe Cyclonic Storm (SS), Storm (S), Depression (D)

Fig. 6(a). Frequency of 24-hr rainfall during Jun-Oct 1901-67

not influence the whole catchment uniformly throughout the period.

Isopleths of pressure departure on 9 October 1941 (Fig. 5e) reveal a range of pressure defect over the catchment about 4 mb and associated catchment rainfall next day was 9.9 cm, while that on 5 October 1936 (Fig. 5f) shows a small pressure defect over most part of the catchment and about 2 mb over its western parts which has contributed to the catchment rainfall of only about 2.8 cm.

This range of pressure defect is measured in this study along a line joining the centre of low (of pressure departure) with Behrampore across the catchment. It is observed that when the low centre lies east of Behrampore even quantitatively lesser values of pressure defect across the catchement prove more effective and contribute to greater rainfall than that when the low centre lies to the west of Behrampore. A graph to this effect is shown at Fig. 7.

Thus a greater range of pressure defect over the catchment for a longer period ensure sustained and heavy rainfall during the next 24 hours and it can be kept in view while assessing the catchment rainfall during next 24 hours for flood forecasting purposes. Low yields of precipitation may be associated with diffused field of isopleth of pressure departures over the catchment.

Maximum 24 hours and 48 hours average storm rainfall—Table 6 contains the maximum 24-hr and 48-hr average rainfall over Bhagirathi catchment. This is also shown graphically in Figs. 6 (a) and (b) respectively. The 24-hr storm rainfall shows a peak between 4 and 5 cm which is the most probable value. The spread towards greater values of rainfall is more than that towards the lower values from the peak. Also the histogram falls more sharply from the peak towards lower values of rainfall than towards higher values of rainfall. This confirms the fact that this peak is mainly contributed by the weaker systems and partly by the stronger systems which may be moving. Relatively, gentle slope towards higher values of rainfall is due to stronger systems affecting Bhagirathi catchment.

The 48-hr average maximum storm rainfall histogram shown in Fig. 6(b) reveals 3 peaks. The first peak between 6 and 7 cm is obviously due to weaker systems while that between 9 and 10 cm is due to relatively stronger systems. But both the peaks are equally probable. Thus it is clear that depending on the intensity of the system and its likely movement 48 hours storm rainfall may be more precisely forecast by the use of this histogram. The third and fourth peaks are due to very strong systems which have travelled very slow

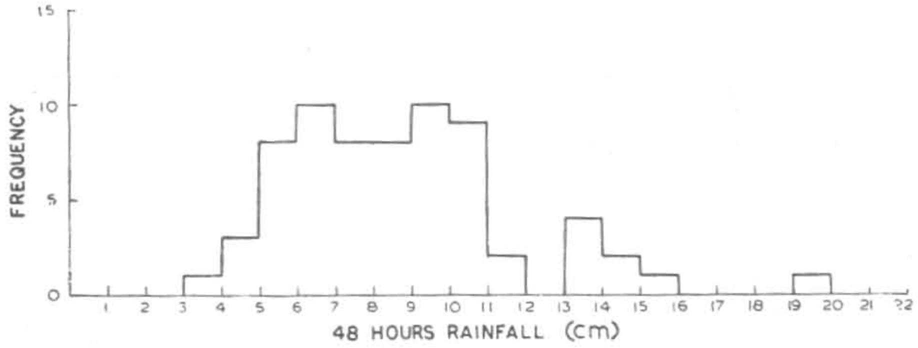


Fig. 6(b). Frequency of 48-hr rainfall during Jun-Oct 1901-67

TABLE 6

Maximum 24-hour and 48-hour average rainfall over Bhagirathi catchment

Year	24-hr (cm)	48-hr (cm)	Year	24-hr (cm)	48-hr (cm)
1901	4·1	5·4	1935	5·7	10·3
1902	7·0	10·6	1936	3·9	7·4
1903	4·9	7·9	1937	5·9	9·4
1904	5·5	8·3	1938	4·0	6·8
1905	8·9	14·5	1939	5·9	11·5
1906	4·9	4·9	1940	3·2	5·1
1907	5·6	9·4	1941	9·9	15·7
1908	6·0	10·6	1942	7·3	10·5
1909	9·8	14·3	1943	8·3	13·6
1910	4·2	6·0	1944	4·6	8·4
1911	7·8	13·5	1945	5·6	11·0
1912	3·1	5·5	1946	5·1	7·4
1913	6·6	9·6	1947	4·2	7·0
1914	5·5	8·3	1948	2·6	4·2
1915	4·2	6·2	1949	3·9	7·0
1916	6·7	13·4	1950	5·9	10·0
1917	7·6	13·1	1951	5·1	9·2
1918	6·1	10·9	1952	3·2	4·7
1919	3·3	6·1	1953	4·7	8·6
1920	7·2	9·7	1954	4·4	6·8
1921	6.5	10·2	1955	3·7	6·7
1922	4·9	9·6	1956	11·5	19·1
1923	3·6	3·6	1957	5·8	9·1
1924	5·3	9·2	1958	3·2	5·2
1925	4·0	6·4	1959	4·8	9·7
1926	4·7	8·6	1960	3·6	5·4
1927	3·1	5·7	1961	4·9	6·5
1928	5·9	10·6	1962	4·5	8·5
1929	4·3	8·5	1963	5·1	6·2
1930	4·8	8·4	1964	2·7	5·3
1931	4·2	7·9	1965	5·8	10·0
1932	3·4	6·1	1966	4·3	7·3
1933	4·7	9·0	1967	3·9	7·2
1934	2·8	5·1			

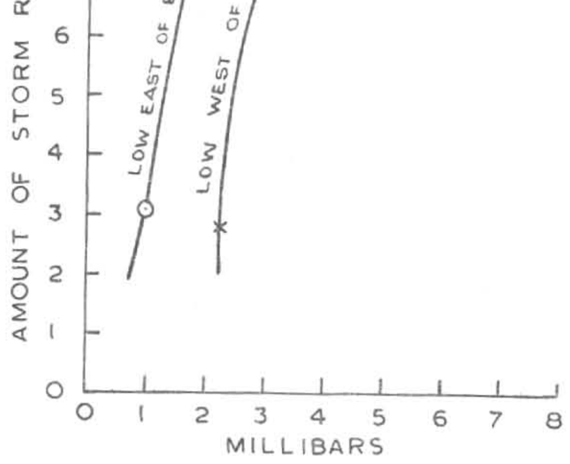


Fig. 7. Range of pressure defect

TABLE 7

Estimation of maximum depth of precipitation for different return periods in Bhagirathi catchment

Return period (T) (years)	24-hour depth of precipitation (cm) ($P_{T'}$)	48-hour depth of precipitation (cm) ($P_{T'}$)
10	7·77	12·90
25	9·21	15·29
50	10·27	17·07
100	11·33	18·81

and affected the catchment for greater time thus contributing very heavy rainfall. Such situations are rather few (about 12 per cent) and it is not difficult to diagnose them.

11. Maximisation factor for the storm of 26 September 1956

With a view to finding the physical upper limit to the magnitude of the flood, it is necessary to know the maximum probable rainstorm. The best known upward adjustment, to be applied to the historically major storm is the maximisation with respect to moisture charge. This adjustment has been applied to the rainstorm of 26 September 1956 (average precipitation depth 11.5 cm). The observatory station available in the storm region was Burdwan whose temperature data for long periods were available. The maximisation factor has been calculated with the dew point temperature of Burdwan :

Maximum dew point temperature at 1004.2 mb pressure	29.4°C
Prevailing dew point temperature at 1010.9 mb pressure	25.0°C
Maximum dew point temperature reduced to 1000 mb pressure	29.3°C
Prevailing dew point temperature reduced to 1000 mb pressure	24.9°C

Maximisation factor, therefore, according to Pramanik and Hariharan (1951) is :

$$\frac{d_1}{d_2} = \frac{4.70}{3\cdot 20} = 1.47$$

where,

d_1 = Depth of precipitable water in a column of air from 1000 mb to 200 mb at maximum dew point temperature.

d_2 = depth of precipitable water in column of air from 1000 mb to 200 mb at prevailing dew point temperature.

Increasing the magnitude of the recorded highest rainstorm by this ratio, a one-day rainstorm of the magnitude of 16.9 cm is not unlikely in the catchment and this value may be taken as the design storm value for the catchment.

12. Return period analysis*

Out of these 238 rainstorms, the heaviest in each year for durations of 1-day and 2-day have been picked out to form an annual maximum series and is given in Table 6 for the purpose of Gumbel extreme value analysis. The estimation equation is given as :

$$P_T = \bar{P} + \sigma \frac{Y_T - \bar{Y}_n}{S_n} \qquad (1)$$

where $Y_T = \log_e \log_e \left[\frac{T}{T\text{-}1} \right]$ and T is the return period in years

Also reduced mean $\bar{Y}_n = .5540$ ⎫ for a sample

Reduced standard deviation $S_n = 1.1824$ ⎭ size $n = 67$

The mean $\bar{P}$ for 24-hr and 48-hr rainfall is 5.20 and 8.62 cm respectively. The standard deviations for the above rainfall values are 1.79 and 2.98.

Using these values in Eqn. (1) the estimation equation for maximum rainfall becomes :

For 24 hours

$$P_{T'} = 1.5155\ Y_T + 4.3604$$

For 48 hours

$$P_{T'} = 2.5237\ Y_T + 7.2220$$

Estimation of maximum 24-hr and 48-hr rainfall obtained form the above equations are given in Table 7.

13. Regression equation for evaluating catchment rainfall

With a view to making the storm study useful for flood forecasting it was thought necessary to develop a regression equation to enable one to evaluate the 24-hr rainfall for the catchment without having to wait for actual rainfall reports from all the stations. Correlation coefficients of 35 stations individually were worked out with the catchment average rainfall by using the avaliable data (by applying Student t- test). Stations, *viz.*, Hiranpur, Burdwan, Sagardihi and Deogarh were found to have correlation coefficients as 0.42, 0.84, 0.61 & 0.46 respectively and are found to be statistically significant. These stations were selected for the purpose of evaluating the regression equation which is given below :

$$Y = 0.11X_1 + 0.16X_2 + 0.05X_3 + 0.04X_4 + 2.3$$

where Y stands for average catchment rainfall for 24-hr and X_1, X_2, X_3 and X_4 stand for observed 24-hr rainfall for the stations Hiranpur, Burdwan, Sagardihi and Deogarh respectively.

This equation was further applied to a set of 40 daily recorded rainfall observations from the 4 individual stations on occasions when the average precipitation depth of the catchment rainfall exceeded or equalled to 2.5 cm, the threshold value chosen for 1-day rainstorm and the average catch-

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*The return period study was made by S/Shri S.D.S. Abbi, K.K. Srivastva, C.M. Anand & Brij Bhushan.

ment rainfall were computed. The result obtained were satisfactory within 10 to 20 per cent.

In order to test the reliability of the regression equation for making immediate calculation of the 24-hr average catchment rainfall with the help of 24-hr rainfall of the 4 stations mentioned above F test was performed. The variance ratio was found to be 1.14 and this was found to be statistically significant at 1 per cent level.

The above test establishes that the regression equation will give reliable estimates of the catchment average rainfall from the rainfall of the 4 stations considered above, whenever and average depth of 2.5 cm or more of rainfall is expected over the catchment judging from the intensity and location of a low pressure system.

14. Conclusions

(*i*) Depressions/storms when they are located in the Bay of Bengal or over land generally between Lats. 17°N and 25°N and Longs. 82°E-92°E cause storm rainfall in the catchment. The depth of the rainstorms vary generally between 3.0 and 5.0 cm depending on the intensity and direction of movement of the system and its proximity to the catchment area. However, rainfall as low as 1.5 cm and as high as 7.1 cm may be realised by these systems.

(*ii*) Land depression which form over Gangetic West Bengal, Bihar and adjoining parts of Madhya Pradesh and eastern Uttar Pradesh cause heavy rainfall amounting to 8.1 cm average precipitation depth over the catchment.

(*iii*) With a view to find the physical upper limit to the magnitude of the highest rainstorm of 26 September 1956(11.5 cm). Maximisation factor of 1.5 has been found, thereby indicating that a rainfall depth of 16.9 cm is not unlikely to occur in the catchment area.

(*iv*) Regression equation has been formulated to obtain the past 24-hr average catchment rainfall using daily rainfall data of Hiranpur, Burdwan, Sagardihi and Deogarh. Data from a large number of stations are not available due to one reason or the other.

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